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Stress Distribution in Composite Flatwise Tension Test Specimens

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STRESS DISTRIBUTION IN COMPOSITE FLATWISE TENSION TEST SPECIMENS

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ABSTRACT

A finite element analysis was conducted to determine the stress distribution in typical graphite/epoxy composite flatwise tension (FWT) specimens under normal loading conditions. The purpose of the analysis was to determine the relationship between the applied load and the stress in the sample to evaluate the validity of the test as a means of measuring the out-of-plane strength of a composite laminate. Three different test geometries and three different material layups were modeled. In all cases, the out-of-plane component of stress in the test section was found to be uniform, with no stress concentrations, and very close to the nominal applied stress. The stress in the sample was found to be three-dimensional, and the magnitude of in-plane normal and shear stresses varied with the anisotropy of the test specimen. However, in the cases considered here, these components of stress were much smaller than the out-of-plane normal stress. The geometry of the test specimen had little influence on the results. It was concluded that the flatwise tension test provides a good measure of the out-of-plane strength for the representative materials that were studied.

INTRODUCTION

The Flatwise Tension (FWT) Test is used to measure the out-of-plane strength of composite laminates. Typically, in this test, solid tabs are bonded to opposite faces of a flat sample from a composite laminate and the sample is loaded in a direction normal to the plane of the laminate (Figure 1). In some cases, a thick specimen is manufactured and machined in order to produce a tapered section, ensuring that failure will occur in that region. Several different sample geometries have been used with the Flatwise Tension Test to characterize the out-of-plane strength of composite laminates [1-3].

A potential problem associated with this test is the non-uniform three-dimensional state of stress in the specimens that can occur due to differences in properties of the tabs and the sample, and stress concentrations due to the geometry of the test configuration. The need for determining the stress distribution in

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samples was noted in a study using thick, tapered samples [3], but is even more critical in cases where the sample is thin relative to the lateral dimensions. The applied load at which the sample fractures can be strongly influenced by stress concentrations, or shear and in-plane normal stresses developed in the sample. An important consideration, therefore, is the relationship between the applied load and the stress distribution in the sample.

The purpose of this study was to compute the stress distribution in typical composite FWT samples, and to use the stress distribution to evaluate the validity of the test as a means of measuring the out-of-plane strength of a composite laminate.

METHODS

The stress in the samples was estimated with a linear finite element (FE) analysis [4]. The finite element models included both the specimen and a portion of the tab. A number of different specimen and tab geometries were modeled. All of the stress components were calculated as a function of position in the sample to determine the relationship between the applied load and the stress distribution in the test specimen.

Model Geometry

Finite element models were constructed to simulate three representative FWT specimen geometries: a 3.25 cm square sample bonded between the faces of 3.0 cm square tabs, leaving a .125 cm overhang around the perimeter of the tab; a 3.0 cm square specimen bonded between the faces of the same 3.0 cm square tabs; and a circular sample with a diameter of 3.0 cm bonded between circular tabs of the same diameter. In all three cases the specimens that were modeled were 1.2 mm thick. Both of the square models and the outer regions of the circular model were constructed entirely of 8-noded isoparametric hexagonal elements (MSC/NASTRAN element CHEXA). The inner 1.5 mm radius of the circular model was made up of 6-noded isoparametric wedge elements (MSC/NASTRAN element CPENTA) due to degeneracies in that region of the model. The finite element models took advantage of the symmetry that exists through the midplane of the test samples. The models included half the sample thickness of .6 mm, and a 1 cm thick aluminum tab. A schematic of the model, including a definition of the coordinate system, for the case of the square sample with an overhang is shown in Figure 2.

Model Material

The tabs were modeled using isotropic elements with the mechanical properties of aluminum. The specimens were modeled using orthotropic elastic finite elements with mechanical properties representing 0.6 FVR T300 graphite/934 epoxy composite laminates laid up in different configurations with .15 mm plies. A total of five different FE simulations were conducted. The square model with the overhang was given three different sets of mechanical properties, corresponding to a unidirectional $[0]_8$ layup, a $[0/(45/-45)_2]_s$ layup and a $[(30/-30)_2/90/\underline{90}]_s$ layup, where the underline indicates the central ply of the laminate. These were chosen based on an ongoing experimental program utilizing these layups. For the square model without the overhang, and the circular model, only the properties of a $[0/(45/-45)_2]_s$ layup were used. Although the mechanical properties were computed based on the above layups, for consistency the thickness dimension of all of the specimens were fixed at 1.2 mm. Mechanical properties were calculated from properties of the fiber and matrix using composite micromechanics and laminate analysis [5] and are shown in Table 1.

Loading and Boundary Conditions

The loading and boundary conditions consisted of a tensile pressure load of 35 MPa applied in the z direction (Figure 2) to the top surface of the tab, while the nodes on the bottom of the model (midplane of the sample) were constrained in the z direction. The applied stress was approximately the same as the failure stress that we have measured for typical samples in this configuration.

RESULTS

In all of the cases modeled the normal stress, σ_{zz}, was relatively uniform throughout the specimens, with no areas of high stress concentration. In the square and circular models without the overhang, the normal stress at the midplane was very close to the nominal applied stress (Figures 3 and 4). It decreased very slightly from the center of the specimen to the edges.

The effects of the overhang on the stress distribution was minimal. In the region between the tabs, the normal stress in the $[0/(45/-45)_2]_s$ specimens was quite uniform (Figure 5), with a distribution that looked similar to the samples without the overhang. In the overhang region it decreased significantly (Figure 6).

The normal stress in the $[(30/-30)_2/90/\underline{90}]_s$ laminate and the unidirectional laminate (Figure 7) were similar. From the center of the specimen to the overhang, the normal stress was relatively constant and comparable to the applied pressure load. Although the stress was lower near the edges of the sample, throughout most of the sample the stress was very close to the applied stress, with the maximum stress being 10% greater than the nominal stress.

The finite element analysis confirmed the three dimensional stress state in the sample. In most cases, components of stress other than the normal stress in the z-direction were much smaller than the nominal applied stress (Figures 3, 4, 6 and 7). For the $[0/(45/-45)_2]_s$ layup, the largest component of out-of-plane normal stress, σ_{yy}, was relatively uniform throughout the sample, with a magnitude of about 13% of the applied normal stress (Figures 3, 4 and 6). For the unidirectional sample the largest component of out-of-plane stress, σ_{xx}, was higher, approximately 38% of the applied normal stress (Figure 7). In all cases the shear stresses were insignificant compared to the nominal applied stress.

DISCUSSION AND CONCLUSIONS

The results of the finite element analysis show that the stress distribution in the samples is relatively uniform and stress concentrations that may produce local failure at low values of nominal stress do not exist. In this respect it appears that, for the materials that were modeled, the Flatwise Tension Test is a good measure of the out-of-plane strength of the material.

In the cases that were modeled, other components of stress were much smaller than the normal stress in the direction of applied load. However, in the $[0]_8$ case, where the greatest anisotropy existed, the maximum in-plane normal component of stress was a significant fraction (approximately 38%) of the out-of-plane stress. It is not clear how the in-plane normal and shear components of stress influence the failure strength. The results presented here indicate that these components of stress are affected by the ply layup. However, experimental studies have shown that ply layup does not affect the measured strength in graphite/epoxy samples [2, 3]. This indicates that the in-plane normal and shear components that results from the normal load are not a significant factor in the measured failure stress. However, more work should be done to evaluate their effects.

The sample geometry does not produce significant differences in results. The choice of sample geometry may therefore be based on other considerations. In some cases, it may be easier to manufacture square specimens than circular. A noteworthy result of the analysis is that a sample which is larger than the tabs does not significantly alter the stress distribution in the region between the tabs. An advantage to using a larger specimen is that flaws introduced by machining the specimen will not affect the behavior between the tabs.

In summary, the analysis indicates that the normal stress at the center of a Flatwise Tension Test specimen is uniform, and very close to the nominal applied stress. The stress state is three dimensional, but in-plane normal components are smaller than the out-of-plane component and shear stresses are negligable. The use of a sample larger than the tabs does not significantly alter the stress state, and has the advantage of eliminating the effects of machining damage. While there is still some question as to the effects of in-plane normal components of stress on the measured strength, the Flatwise Tension Test appears to provide a good measure of the out-of-plane strength for the representative materials that were studied.

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Table 1. Mechanical properties for specimens used in the analysis.

	$[0/(45/-45)_2]_s$	$[(30/-30)_2/90/\underline{90}]_s$	$[0]_8$
E_{11} (MPa)	3.91 x 10^4	5.34 x 10^4	1.34 x 10^5
E_{22} (MPa)	2.26 x 10^4	4.33 x 10^4	8.73 x 10^3
E_{33} (MPa)	1.02 x 10^4	1.03 x 10^4	8.73 x 10^3
G_{12} (MPa)	2.86 x 10^4	2.08 x 10^4	4.10 x 10^3
G_{23} (MPa)	3.12 x 10^3	3.21 x 10^3	2.48 x 10^3
G_{13} (MPa)	3.45 x 10^3	3.36 x 10^3	4.1 x 10^3
ν_{12}	.77	.38	.26
ν_{23}	.23	.27	.42
ν_{31}	.02	.05	.02

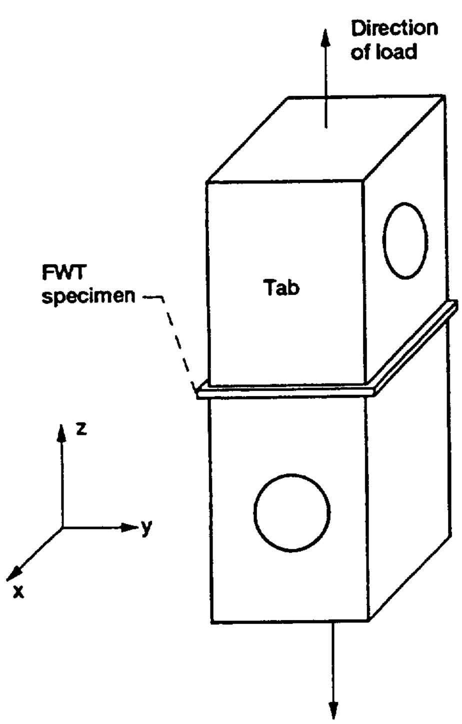

Figure 1.—Schematic of typical flatwise tension test configuration.

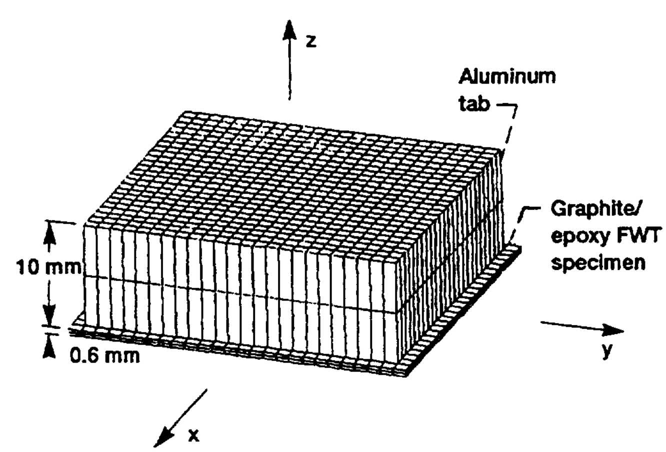

Figure 2.—Finite element model of the specimen and tab for the case where the specimen is larger than the tab. The results of the analysis are given in the coordinate system shown.

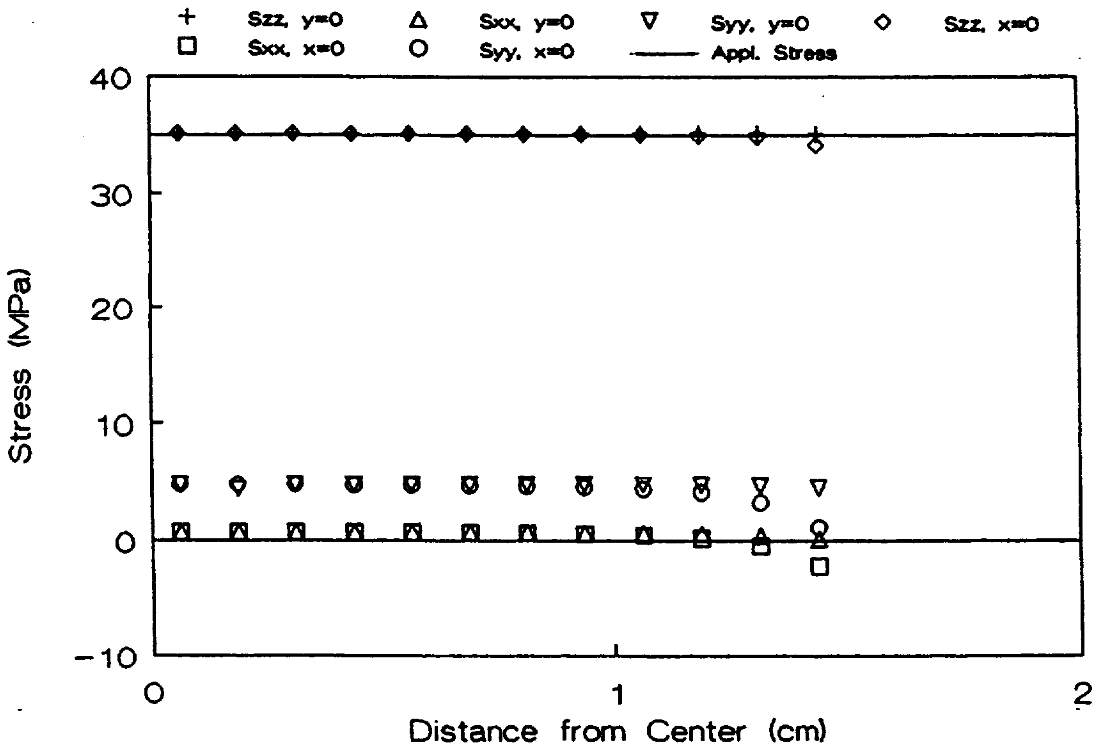

Figure 3.—Normal and in-plane stress along the x and y axes at the mid-plane of the $[0/(45/-45)_2]_s$ sample without the overhang, compared with the nominal applied stress. The normal component is uniform and very close to the nominal applied stress. In-plane normal components of stress are relatively small.

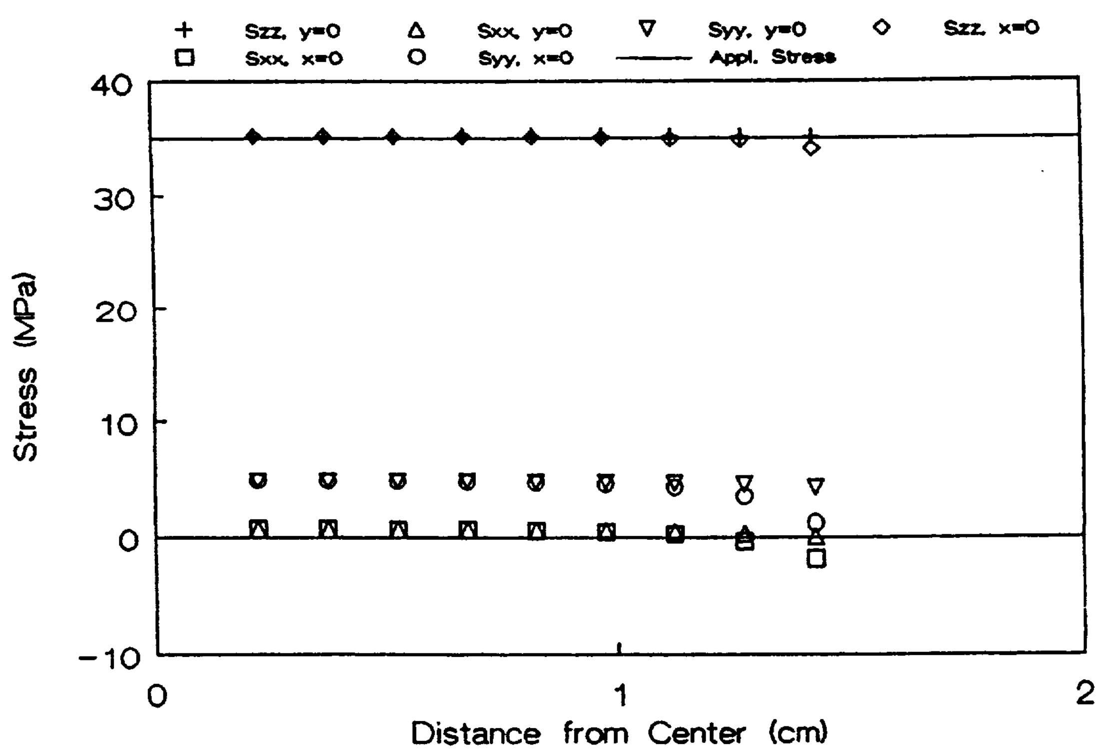

Figure 4.—Normal and in-plane stress along the x and y axes at the mid-plane of the circular $[0/(45/-45)_2]_s$ sample, compared with the nominal applied stress. The normal component is uniform and very close to the nominal applied stress. In-plane normal components of stress are relatively small.

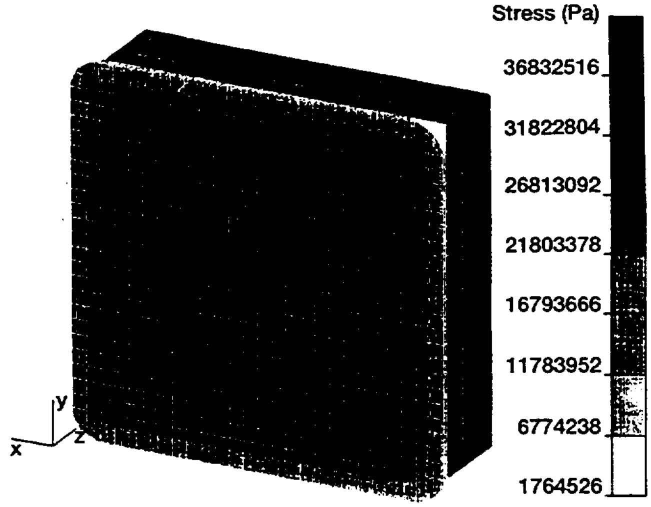

Figure 5.—Shaded diagram of the out-of-plane stress distribution at the mid-plane of the $[0/(45/-45)_2]_S$ sample with the overhang. In the region between the tabs, indicated by dashed lines, the stress is very uniform.

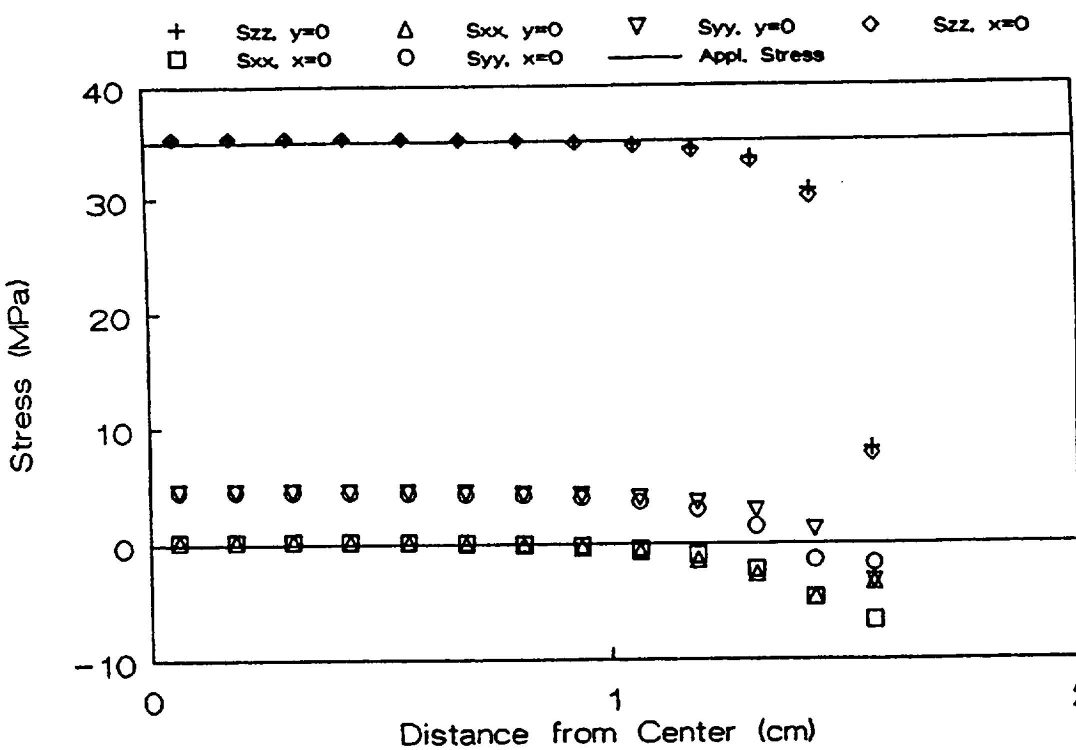

Figure 6.—Normal and in-plane stress at the mid-plane of the $[0/(45/-45)_2]_s$ sample with the overhang, compared with the nominal applied stress. The computed stress in the region between the tabs is uniform and very close to the nominal applied stress. The overhang has minimal influence on the stress distribution.

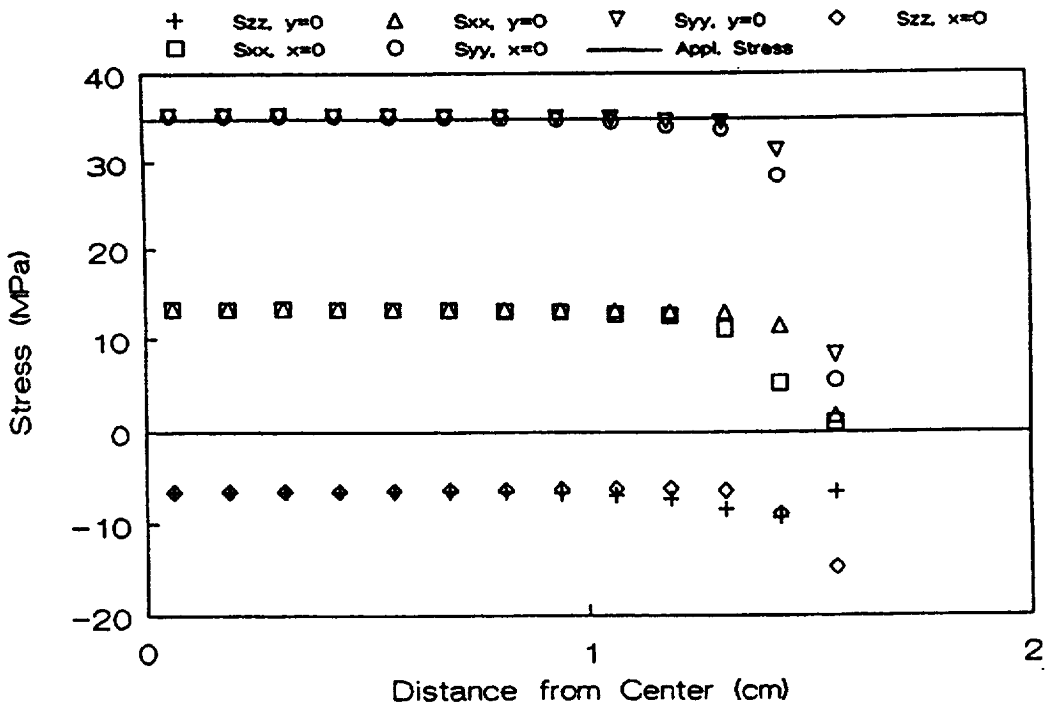

Figure 7.—Normal and in-plane stress at the mid-plane of the $[0]_8$ sample with the overhang, compared with the nominal applied stress. The computed stress in the region between the tabs is uniform and very close to the nominal applied stress. The in-plane normal component of stress, σ_{xx}, for this sample is higher than in other samples studied.

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13. ABSTRACT *(Maximum 200 words)*

A finite element analysis was conducted to determine the stress distribution in typical graphite/epoxy composite flatwise tension (FWT) specimens under normal loading conditions. The purpose of the analysis was to determine the relationship between the applied load and the stress in the sample to evaluate the validity of the test as a means of measuring the out-of-plane strength of a composite laminate. Three different test geometries and three different material layups were modeled. In all cases, the out-of-plane component of stress in the test section was found to be uniform, with no stress concentrations, and very close to the nominal applied stress. The stress in the sample was found to be three-dimensional, and the magnitude of in-plane normal and shear stresses varied with the anisotropy of the test specimen. However, in the cases considered here, these components of stress were much smaller than the out-of-plane normal stress. The geometry of the test specimen had little influence on the results. It was concluded that the flatwise tension test provides a good measure of the out-of-plane strength for the representative materials that were studied.

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